Dense optical and near-infrared monitoring of CTA 102 during high state in 2012 with *OISTER*: Detection of intra-night "orphan polarized flux flare"

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ABSTRACT

CTA 102, classified as a flat spectrum radio quasar at z=1.037, produced exceptionally bright optical flare in 2012 September. Following *Fermi*-LAT detection of enhanced γ-ray activity, we densely monitored this source in the optical and near-infrared bands for the subsequent ten nights using twelve telescopes in Japan and South-Africa. On MJD 56197 (2012 September 27, 4-5 days after the peak of bright γ-ray flare), polarized flux showed a transient increase, while total flux and polarization angle remained almost constant during the "orphan polarized-flux flare". We also detected an intra-night and prominent flare on MJD 56202. The total and polarized fluxes showed quite similar temporal variations, but PA again remained constant during the flare. Interestingly, the polarization angles during the two flares were significantly different from the jet direction. Emergence of a new emission component with high polarization degree (PD) up to 40% would be responsible for the observed two flares, and such a high PD indicates a presence of highly ordered magnetic field at the emission site. We discuss that the well-ordered magnetic field and even the observed directions of polarization angle which is grossly perpendicular to the jet are reasonably accounted for by transverse shock(s) propagating down the jet.

Subject headings: Galaxies: jets

1. Introduction

Blazars are highly variable active galactic nuclei (AGN) emitting radiation at all wavelengths from radio to γ-rays. They have strong relativistic jets aligned with the observer's line of sight and are apparently bright due to relativistic beaming. Their emission typically consists of two spectral components. One is attributed to synchrotron radiation at lower energies peaking in the radio through optical bands, and the other is inverse Compton scattering peaking in the γ-ray bands. Outstanding characteristics of blazars are their rapid and high-amplitude intensity variations or flares. These variabilities are observed in various wavelengths and time scales. Micro variability (intra-day variability) of flux in the optical band has been also detected on timescales as short as minutes to hours (e.g., Racine 1970; Miller & Noble 1996). It is important to measure the time scales of micro variability because it provides limits on the size and location of the emitting regions.

Polarized radiation is one of the evidences of synchrotron origin in low energies and it also varies drastically. Therefore, optical polarimetric observations also provide a strong tool to probe jet structures (e.g., Marscher et al. 2008; Abdo et al. 2010a). Nevertheless, simultaneous short-term (intra-day) observations of flux, color and polarization have been performed only in a few blazars (e.g., Andruchow et al. 2003; Cellone et al. 2007; Sasada et al. 2008; Hagen-Thorn et al. 2008; Andruchow et al. 2011), and hence the origin of micro variability is still unclear.

CTA 102 (also known as PKS J2232+1143, R.A. $= 22^h32^m36.4^s$, decl. $= +11^\circ\ 43'\ 50''.8$, J2000, z=1.037, Hewitt & Burbidge 1989) was first identified as a strong radio source (Harris & Roberts 1960) and classified as a flat spectrum radio quasar (FSRQ, Abdo et al. 2010b) from multi-wavelength observations. CTA 102 showed micro variability of optical flux and color in the 2004 flare (Osterman Meyer et al. 2009). In this flare, the "redder when brighter" trend was reported and it was able to be explained by the superposition of

variable synchrotron component from radio to optical bands and non-variable "blue bump" component which is thought to be thermal disk radiation connecting to the UV band.

Recently, CTA 102 showed an extreme activity in the optical and GeV γ-ray bands on September 2012 (Larionov et al. 2012; Orienti & D'Ammando 2012). In this paper, we present results of high-temporal-density monitoring observations of CTA 102 just after the September 2012 γ-ray flare.

2. Observation

Observations were carried out as a ToO program of Optical and Infrared Synergetic Telescopes for Education and Research (*OISTER*). *OISTER* is a global observing network that links organically many ground-based small telescopes in Japan, South Africa, and Chile under a Japanese interuniversity cooperation regime. *OISTER* is aimed at investigating potential transient sources (γ-ray bursts, AGNs, supernovae, cataclysmic variables, and so on). The biggest advantage of *OISTER* is its capability of performing continuous and high-temporal-density monitoring in many bands extending to as long a wavelength as $K_{\rm s}$. ToO observation of CTA 102 with *OISTER* was conducted from September 23 to October 3 in 2012, following the bright GeV γ-ray flare. We obtained the B, V, g', r', $R_{\rm C}$, $I_{\rm C}$, i', z', J, H, K' and $K_{\rm s}$ band photometric and the $R_{\rm C}$ band polarimetry data with *OISTER* and also with other collaborative telescopes. Telescopes and instruments used for this observation are listed on Table 1. Note that we treated the r' and K' band data as the $R_{\rm C}$ and $K_{\rm s}$ band data, respectively. Reductions of optical and near-infrared (NIR) data were performed under the standard procedure of CCD photometry. The position of comparison star is R.A. = $22^h32^m41.5^s$, decl. = $+11^\circ\ 43'\ 14''.1$ (J2000). The magnitudes in the optical bands were obtained differentially with nearby comparison stars which have been calibrated with the photometric standard stars in Landolt fields (Landolt 1992) observed on clear

Table 1: Observatories, Telescopes and Instruments

Observatory/Telescope	diameter[a]	Instrument	Filters
		Opt/NIR in Japan	
Nayoro Observatory/Pirka	160 cm	MSI[(1)]	V, $R_{\rm C}$
Akeno Observatory/MITSuME[(2)]	50 cm		g', $R_{\rm C}$, $I_{\rm C}$
Kyoto University/–	40 cm		$R_{\rm C}$
Koyama Astronomical Observatory/Araki	130 cm	ADLER	B, g', V, $I_{\rm C}$, i', z'
Nishi-Harima Astronomical Observatory/Nayuta	200 cm	NIC	$K_{\rm s}$
Bisei Spaceguard Center/–	100 cm	Volante	r'
Okayama Astrophysical Observatory/–	188 cm	ISLE[(3,4)]	J, H, $K_{\rm s}$
Okayama Astrophysical Observatory/MITSuME[(2)]	50 cm		g', $R_{\rm C}$, $I_{\rm C}$
Higashi-Hiroshima Observatory/Kanata	150 cm	HOWPol[(5)]	V, $R_{\rm C}$, $R_{\rm C}$-Pol.
Iriki Observatory/–	100 cm	Infrared Camera	J, H, K'
		Opt/NIR in South-Africa	
South African Astronomical Observatory/IRSF	140 cm	SIRIUS	J, H, $K_{\rm s}$
		Radio Observatory	
Mizusawa VLBI Observatory/Hitachi 32-m Telescope	32 m		8.4 GHz

[a] Size of primary mirror

References. — (1) Watanabe et al. 2012; (2) Kotani et al. 2005; (3) Yanagisawa et al. 2006; (4) Yanagisawa et al. 2008; (5) Kawabata et al. 2008.

and stable nights. The same comparison stars are used also in NIR bands, where the magnitude is given in the *2MASS* catalogue (Skrutskie et al. 2006). We corrected the data for the Galactic extinction (e.g., $A_{\rm V}$=0.233, Schlafly & Finkbeiner 2011, NED database[1]). There were small systematic difference in photometric system among observatories and instruments; the standard deviations of the magnitudes of the comparison star during the observation period were $\Delta R_{\rm C} \sim 0.02$ mag ($\sim 2\%$ of flux) and $\Delta K_{\rm s} \sim 0.06$ mag ($\sim 5\%$ of flux). These values were added to the photometric errors of CTA 102 in each band.

The polarimetric observations were performed with HOWPol installed to the Kanata Telescope located on Higashi-Hiroshima Observatory (Kawabata et al. 2008). A unit of the observing sequence consisted of successive exposures at 4 position angles of a half-wave plate; $0^\circ, 45^\circ, 22.5^\circ$ and 67.5°. Polarimetry with HOWPol suffers from large instrumental polarization ($\Delta p \sim 4\%$) produced by the reflection of the incident light on the tertiary mirror of the telescope. The instrumental polarization was modeled as a function of the declination of the object and the hour angle at the observation, and we subtracted it from the observation. We estimated that the error in this instrumental polarization correction is smaller than 0.5% from many observations for unpolarized standard stars. The polarization angle (PA) is defined in the standard manner as measured from north to east. The PA was calibrated with two polarized stars, HD183143 and HD204827 (Schulz & Lenzen 1983). Because the PA has an ambiguity of $\pm 180^\circ \times n$ (where n is an integer), we selected n which gives the least angle difference from the previous data, assuming that the PA would change smoothly. The error of PA was estimated to be smaller than 2° from observations of the polarized stars.

The radio data were obtained from September 26 to 28 using Hitachi 32 m telescope of Mizusawa VLBI Observatory, NAOJ, which is operated by Ibaraki University. The front

[1]http://ned.ipac.caltech.edu/

end was a cooled HEMT receiver, and a typical system temperature was 25 K including the atmosphere toward the zenith. Since beam switching system is not equipped, we rapidly scanned the antenna around the target CTA 102 in azimuth and elevation direction, while recording the total power. As a result, fluctuation of the observed power due to the atmosphere can be minimized and the pointing error can disappear. The accuracy of the calibration was estimated to be 10%.

3. Results

Figure 1 shows temporal variations of the optical $R_{\rm C}$-band and NIR $K_{\rm s}$-band total fluxes, as well as those of the $R_{\rm C}$-band PD and PA during our dense monitoring of CTA 102, following intense γ-ray flare detected by *Fermi*-LAT. In the third panel of Figure 1, we also show a light curve of $R_{\rm C}$-band polarized flux (PF), which was calculated by

$$PF = \frac{PD \times F_{\rm R_C}}{100}, \tag{1}$$

where PD and $F_{\rm R_C}$ are the measured polarization degree in unit of % and total flux in the $R_{\rm C}$ band. Except for some nights with bad weather, we were able to monitor CTA 102 continuously. We note that, although not shown here, light curves in other bands exhibited quite similar temporal variations to those in the $R_{\rm C}$ and $K_{\rm s}$ bands.

First, the light curves in the $R_{\rm C}$ and $K_{\rm s}$ bands showed a clear decay on MJD 56194. Given that *Fermi*-LAT detected a strong γ-ray flare on MJD 56189, the observed declining profile likely corresponds to the decay phase of the bright γ-ray flare. After that, both of the light curves showed a mild and symmetrical enhancement peaking around MJD 56198 until the end of this follow-up observation, except an intra-night strong flare on MJD 56202. In addition, we can clearly see some remarkable features in the daily polarimetric data. Namely, possible PA swing from $\sim 0^\circ$ to $\sim 100^\circ$ was observed on MJD 56195 and

56196. To check the temporal evolution of the PA, we plotted the Stokes parameters Q and U observed during these nights in Figure 2, together with those of other nights. Again, gradual rotation of PA was obviously seen, confirming the PA swing by $\sim 100^{\circ}$ during these two nights.

The continuous PA rotation was terminated by a sudden jump to $\sim 50^{\circ}$ on MJD 56197. More strikingly, the PF rapidly increased by three times from $\sim 0.1 \times 10^{-11}$ erg cm^{-2} s^{-1} to $\sim 0.3 \times 10^{-11}$ erg cm^{-2} s^{-1} without an apparent increase of the total flux during the night. This is the first clear detection of a short-term (hours-scale) PF flare without corresponding total flux enhancement. Another interesting feature is a strong intra-night flare detected on MJD 56202. The isolated flare showed smooth and symmetrical profile peaking around 13 UT, and the total and polarized fluxes increased by factors of ~1.5 and ~2.0, respectively. Notably, the PD evolved in a quite similar way as the total flux, while the PA remained almost steady during the flare (see also Figure 1 and Figure 2). The PA measured on MJD 56202 is orthogonal to the jet direction observed from VLBA observation (Fromm et al. 2012). This is in contrast with the case of AO 0235+164, in which the optical PA aligned nearly the same direction as the jet during the flare in 2006 December (Hagen-Thorn et al. 2008).

To see spectral evolution in the optical and NIR bands, we plotted $R_{\mathrm{C}} - K_{\mathrm{s}}$ color against R_{C}-band magnitude in Figure 3. As reported in Osterman Meyer et al. (2009), a "redder when brighter" trend is excepted in micro variability. As a result, however, there is no clear correlation between $R_{\mathrm{C}} - K_{\mathrm{s}}$ color and R_{C}-band magnitude for a whole data. Looking at the colors measured during our observation other than MJD 56197 and 56202, the source showed a hint of "redder when brighter" trend, as is reported previously by Osterman Meyer et al. (2009).

On the other hand, radio fluxes were almost constant within 10% during our monitoring

and were comparable to that measured in the quiescent state (Stanghellini et al. 1998). This is because the emission region would be optically thick at 8.4 GHz. Actually, the constant radio flux during optical and γ-ray flare was previously observed for CTA 102 in 2006 (Fromm et al. 2011).

4. Discussion

On MJD 56197, a transient PF flare without significant increase of the total flux was observed. This "orphan PF flare" is interesting and explained in such way that a new emission component which is less luminous but possesses extremely high PD with respect to the long-term baseline component might have emerged suddenly. Large discrepancy of PA between MJD 56196 and 56197 ($\sim 100°$ to $\sim 45°$) supports the emergence of the new component. A careful inspection of the light curve showed that the source brightened only by $\sim$10% in the total flux (which corresponds to $\sim 0.2 \times 10^{-11}$ erg cm^{-2} s^{-1}) during the intra-night increase of PF from 0.1×10^{-11} erg cm^{-2} s^{-1} to 0.3×10^{-11} erg cm^{-2} s^{-1}, implying that the new component has the PD of $\sim$100%. To overcome this unrealistic situation, we have to consider that decrease of total flux of the long-term component occurred simultaneously with the emergence of the highly-polarized new emission component and weakened increase of the total flux. In this case, the PD of the new component depends on how much total flux of the long-term component decreases. For example, we assume that gradual decrease of total flux of the long-term component by 0.2×10^{-11} erg cm^{-2} s^{-1} occurred simultaneously with gradual increase of the new component by 0.4×10^{-11} erg cm^{-2} s^{-1} Then, the PD of the new component can be estimated as 50%, which seems reasonable compared to the above $\sim$100% PD scenario, though still very high. We note that some blazars such as OJ 287 and BL Lac exhibited similar orphan PF flares in longer day-month timescale (Ikejiri et al. 2011). It is currently unclear whether the same

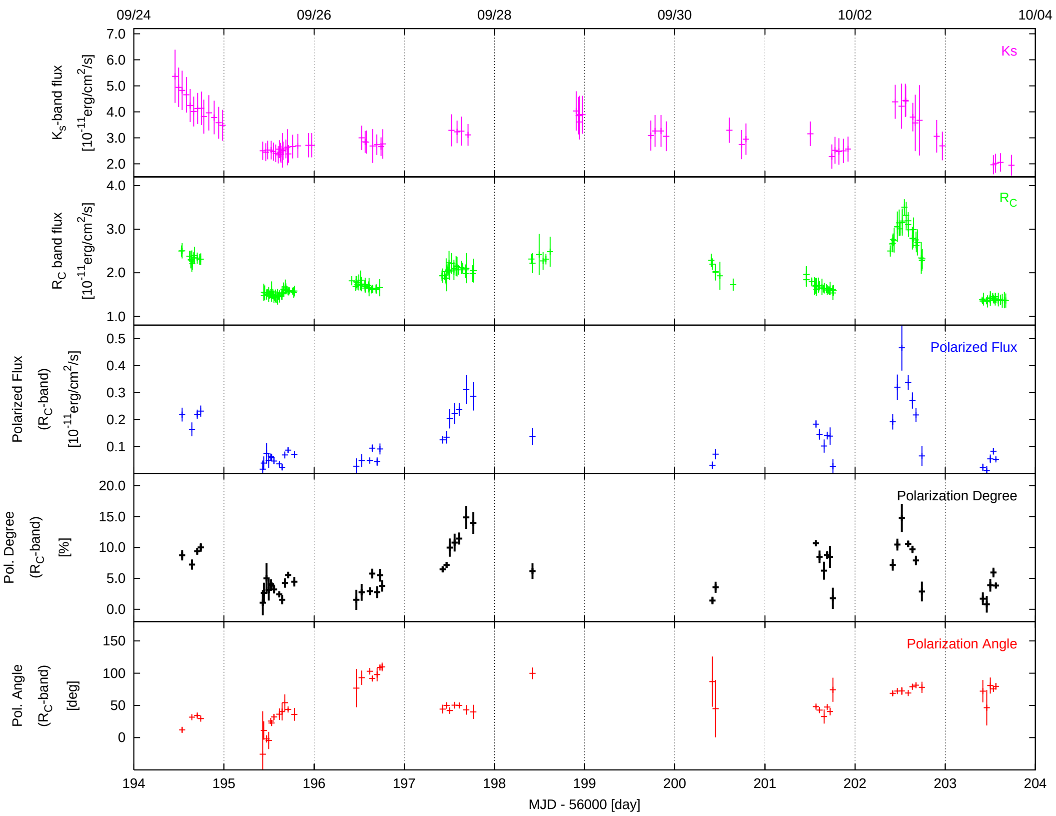

Fig. 1.— Multi-wavelength light curves of CTA 102 from September 24 to Octobe r 3 in 2012. Top panel: NIR (K_s-band) flux. Second panel: optical (R_C-band) flux. Third panel: polarized flux (PF) in the R_C band. Fourth panel: polarization degree (PD) in the R_C band. Bottom panel: polarization angle in the R_C band.

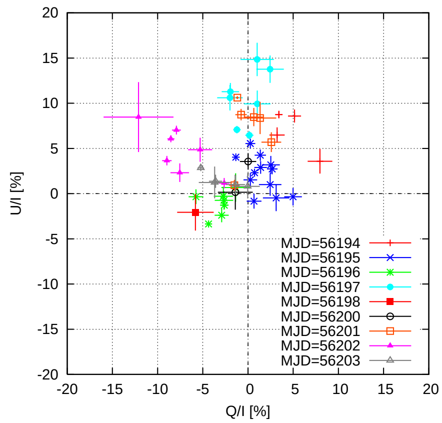

Fig. 2.— Intra-night and daily variations of the Stokes parameters Q and U obtained by Kanata/HOWPol in our observation. Data points of the same color suggest the measurement on the same day. Dashed line (black) indicate the origin of the Stokes parameters.

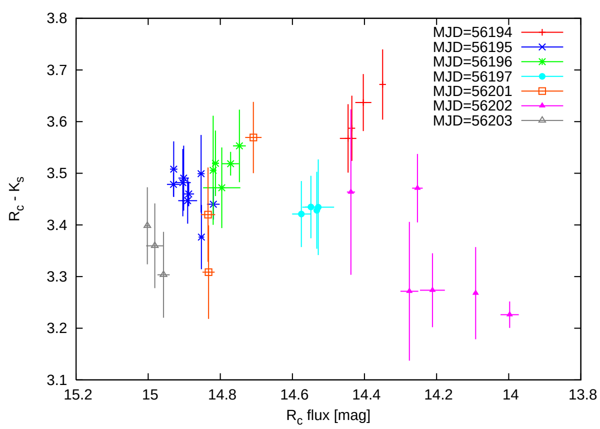

Fig. 3.— Intra-night and daily variations of $R_{\mathrm{C}}-K_{\mathrm{s}}$ color against R_{C}-band flux. Each mark show the same date as those used in Figure 2.

mechanism is responsible for such a similar phenomenon with longer timescale. Anyway, our observation presented here is the first measurement of the orphan PF flare in much shorter (intra-night) timescale, and further theoretical study is needed.

Smooth and continuous change of PA from $\sim 0^\circ$ to $\sim 100^\circ$ observed on MJD 56195 and 56196 suggests either the presence of helical magnetic field inside a jet (Marscher et al. 2008) or global bending of a jet (Abdo et al. 2010a). Note that the PD remained constant at $\sim 3\%$ during the PA swing, which was also observed in both of the two scenarios from BL Lac (helical magnetic field) and 3C 279 (bent jet). The observed large PA swing rate of $\sim 50^\circ$ per day is similar to the case of BL Lac and four times larger than that of 3C 279, implying that the helical magnetic field scenario might be preferred. On the other hand, if PA swing in the opposite direction is observed, the bent jet scenario would be validated.

Current Very Long Baseline Interferometry (VLBI) polarization observation is now feasible to examine magnetic field structure of the parsec-scale jet. Especially, measurement of Faraday rotation is recognized as a powerful tool to manifest the presence of helical magnetic field. When polarized radiation propagates within a magnetized plasma, the plane of linear polarization rotates and the rotation measure (RM, rotation of the polarization angle) depends on the line-of-sight component of the magnetic field (see e.g. Chen 1974). Hence, if helical magnetic field is surrounding the jet, RM gradient across the jet should be observed (e.g. Blandford 1993). Indeed, several authors (e.g., Gabuzda et al. 2004) claimed detection of RM gradient transverse to the VLBI jet in various blazars since the first discovery from 3C 273 by Asada et al. (2002), although the significance of these detections is still controversial (Taylor & Zavala 2010). Importantly, recent Very Long Baseline Array (VLBA) observation detected significant RM gradient from CTA 102 (Hovatta et al. 2012). The presence of helical magnetic field is consistent with our observation of relatively fast PA swing over the two nights on MJD 56195 and 56196. Thus, optical polarimetry provides

another powerful tool to claim the presence of helical magnetic field.

A prominent brightening was observed on MJD 56202, as is evident from the light curves of both the total flux and PF, with almost constant PA of $\sim 70^\circ$ (see Figure 1). This could be again explained by emergence of a new bright component with high PD with respect to the long-term baseline emission component. Comparison of the total and polarized fluxes between the beginning and peak of the flare allows us to estimate the PD of the new component. Namely, ratio of the PF increase by $\sim 0.35 \times 10^{-11}$ erg cm^{-2} s^{-1} with respect to the total-flux increase by $\sim 1.0 \times 10^{-11}$ erg cm^{-2} s^{-1} leads to the PD of $\sim$30–40% for the new emission component. Such a high PD indicates presence of highly ordered magnetic field at the emission site, which might be generated through compression of turbulent magnetic field by shocks inside a jet as advocated by previous papers (e.g., Hagen-Thorn et al. 2008).

The optical PAs measured during the two flares on MJD 56197 and 56202 were $\sim 45^\circ$ and $\sim 70^\circ$, respectively. Compared to the VLBA jet image (see e.g. Fig.A.15 of Fromm et al. 2013, for the jet image), we found that they are nearly orthogonal to the jet direction. Since magnetic field direction is in principle assumed to be perpendicular to PA, the measured PAs result in a claim of magnetic field orientation aligned with the jet. How is the highly-ordered magnetic field aligned with the jet generated? At first glance, the shock-in-jet scenario considered above seems unreasonable, because the magnetic field compressed by shocks propagating down the jet is aligned with a direction transverse to the jet. It should be noted that here magnetic field direction is inferred based on the assumption that it is orthogonal to the observed PA but recent theoretical work suggests that such an assumption is not correct for relativistically moving sources like AGN jets (Lyutikov et al. 2005). In particular, Lyutikov et al. (2005) pointed out that toroidally dominated magnetic field is observed as poloidal in the observer's (rest) frame when ultra-relativistic jet with

$\Gamma >> 1$ is viewed at small angle to the line of sight (Γ is bulk Lorentz factor of the jet). Given this complicated situation, the measured EVPAs significantly different from the jet direction can still be accounted for by the "shock-in-jet" scenario.

It is interesting to compare the PAs observed during the two flares on MJD 56197 and 56202 with past observation, although only one observation by Hagen-Thorn et al. (2008) is found in the literature. The authors reported hours-scale short timescale polarimetric variability from BL Lac object AO 0235+164 during an outburst in 2006 December and found that the PAs tend to align with the jet direction around the maximum PD (see Fig. 4 of Hagen-Thorn et al. 2008). This is quite different from our observation of perpendicular EVPAs to the jet direction. If relativistic effect hypothesis is true, uniform distribution of EVPA with respect to the jet direction would be found for hour-scale flares. In any case, the current samples are only two and further optical polarimetric observation is definitely needed.

To summarize, we performed dense optical/IR photometric and polarimetric monitoring of CTA 102 following strong γ-ray flare in 2012 September with *OISTER* program. We found (i) smooth and gradual PA swing by ~ 100 deg over the two nights on MJD 56195 and 56196, (ii) orphan polarized flux flare on MJD 56197, (iii) significant brightening on MJD 56202 and (iv) grossly perpendicular PAs to the jet direction during the two flares. Combined with recent VLBA detection of RM gradient across the jet, we infer that helical magnetic field would be present at the emission region responsible for the long-term baseline component. The observed two flares can be explained by emergence of new emission component which possess highly-ordered magnetic field. Such a magnetic field configuration would be generated through compression by shocks propagating down the jet. The observed EVPAs perpendicular to the jet direction is not unreasonable given the effect of relativistically-moving radiation source.

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